Simulation of Complex, Unsteady Flows Using a Grid-Free Vortex Method

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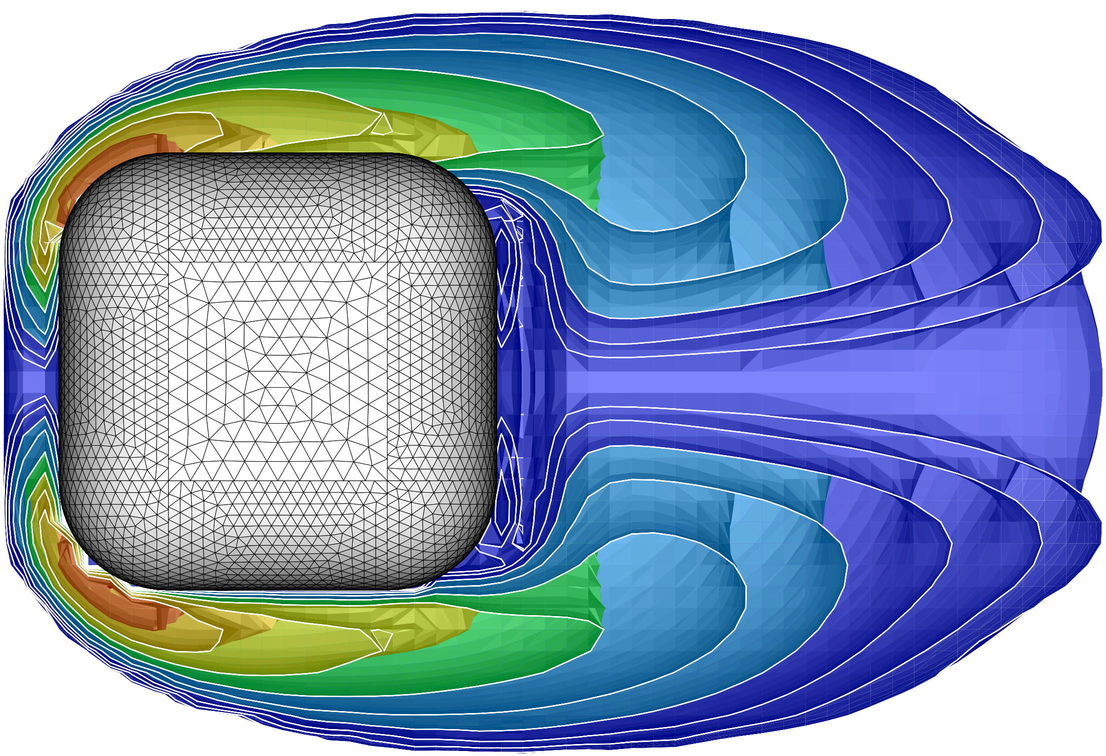
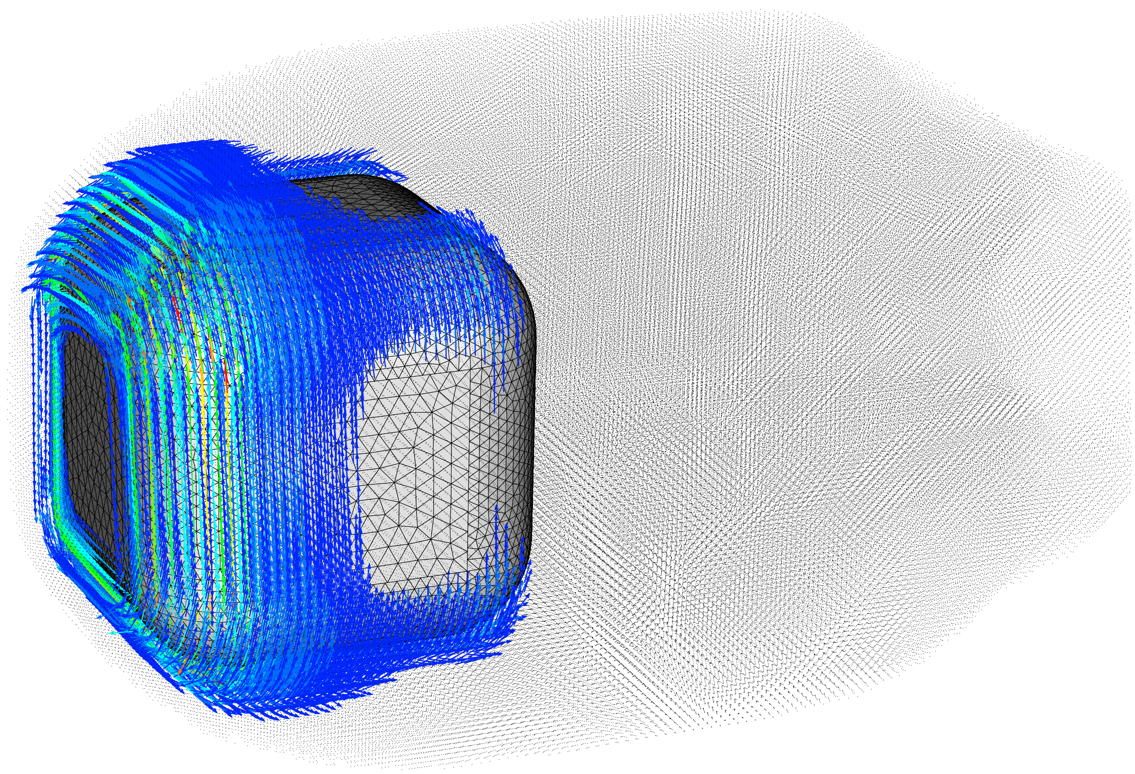
Essentials

- Numerical technique to solve the Navier-Stokes Equations
- Suitable for Direct Simulation and Large-Eddy Simulation
- Uses vorticity (curl of the velocity) as a variable
- Computational elements move with the fluid velocity



Advantages

- Computational elements only where vorticity is non-zero
- No grid in the flow field
- Only 2D grid on vehicle surface
- Boundary conditions in the far field automatically satisfied



Vortex Method as a Flow Model

Previous limitations (1960s and 70s)

- Inviscid model – dynamics of the boundary layer ignored
- Computationally limited – $O(N^2)$ operations per time step
- $N =$ only a few hundred to a few thousand computational elements feasible
- Dynamics of the wake and force coefficients dependent on adjustable parameters

Recent Developments (90s)

- Viscous effects treated accurately
- Fast Vortex Algorithm – $O(N \log N)$ operations per step
- $N =$ one to 100 million computational elements feasible
- Dense system of computational elements solves fluid equations
  - Direct simulation for low Reynolds number
  - Large-Eddy simulation for high Reynolds number
- Large-scale, load-balanced parallel computing

Treatment of Surface Vorticity

Standard Panel Method for N Panels

- Computationally and storage limited – $O(N^2)$ matrix elements computed and stored with $O(N^2)$ operations per time step
- Only $N = 10,000$ to $20,000$ feasible

Advanced Panel Method

- Extendible to high order accuracy
- Computationally efficient – $O(N)$ storage locations with $O(N \log N)$ operations per time step
- $N = 10^6$ no problem
- Triangular mesh with automatic refinement

Large-Eddy Simulation

Direct Simulation not Sufficient (1990s)

- Direct Simulation possible for Reynolds no.=10^3 to 10^4 (at parking speeds – 0.01 mph)

- $N = 10^{12}$ elements (approx. 20 Terabytes) required for Reynolds no.=5×10^6
  (at highway speeds)

Large-Eddy Simulation Required

- Treatment of small-scale (subgrid-scale) turbulence in the wake

- Treatment of small-scale turbulence in the boundary layers

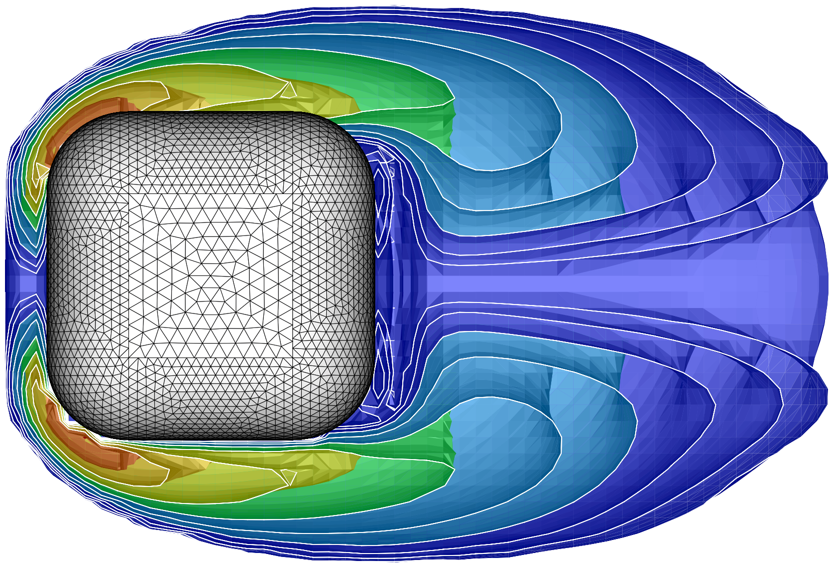
- Treatment of fluidic actuators, blowing/suction, vortex generators and other flow control devices

Rounded Cube DNS

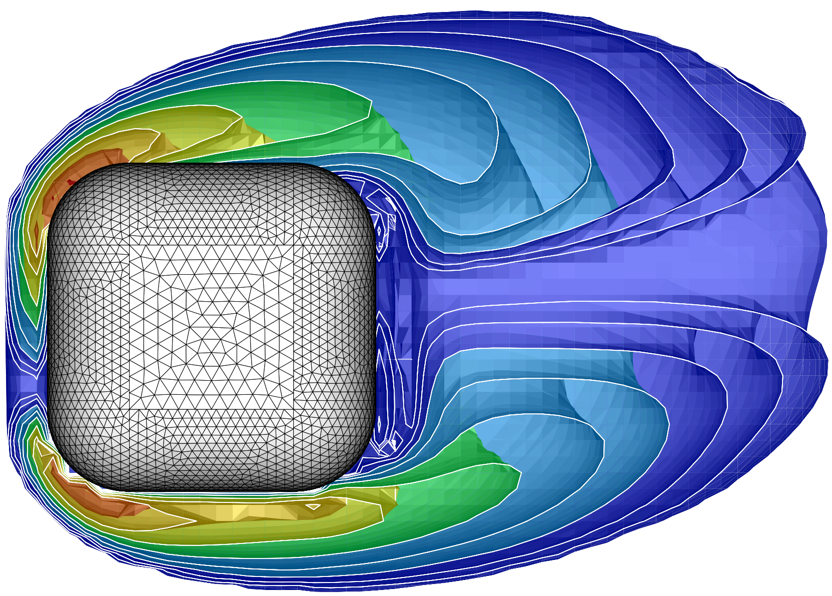
Features

- Adjustable leading edge curvature
- 0, 10 deg. yaw
- Reynolds no. 100
- Body forces

Vorticity Contours



0 deg.



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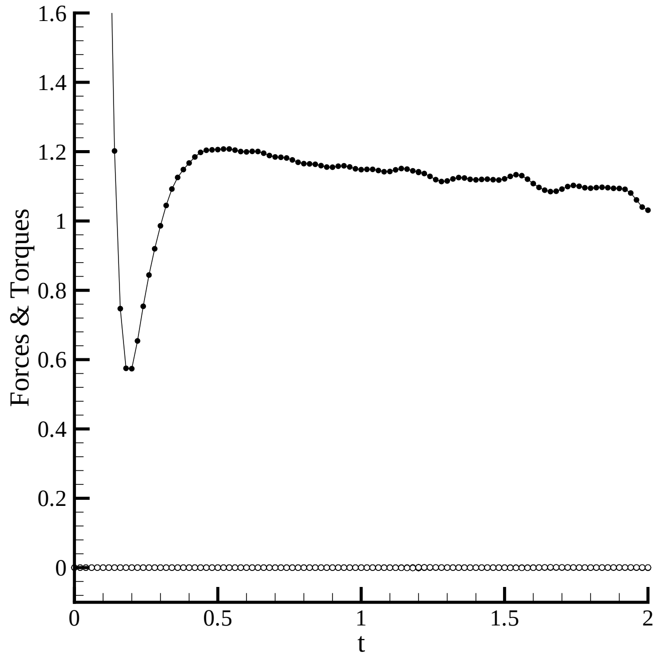
Body Forces



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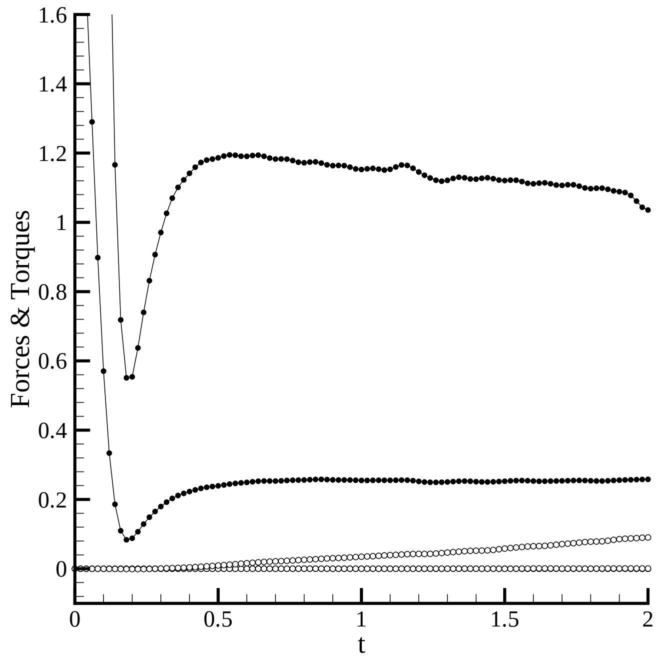

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Status / Future Work

- Incorporation of GTS model into full Vortex Method
- Implementation of the Vortex Method for arbitrary complex geometries
- Analysis of Reynolds number effects (leading edge curvature)
- Subgrid stress model for Large-Eddy Simulation